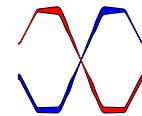


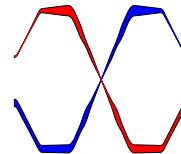
Crabs in LHC



Rama Calaga
Rogelio Tomás, Frank Zimmermann

Thanks: Joachim Tuckmantel

LHC-LUMI 06 - Oct 17th, 2006

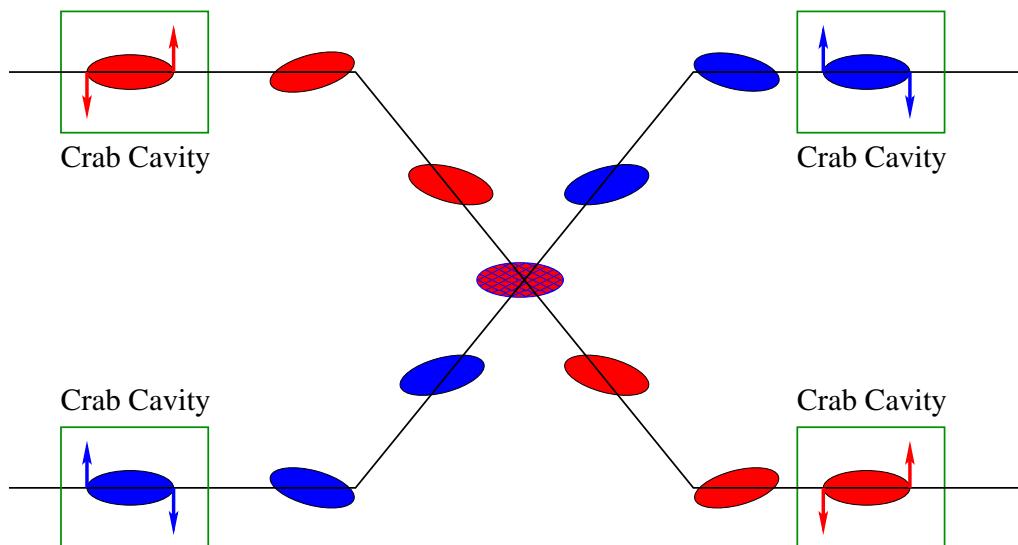


Topics

- History & Motivation
- Global or Local IR Cavities
 - Orbit Excursion
 - Tune Spread
- Emittance Growth
 - RF Curvature, Amplitude and Phase Noise
 - Energy Spread, Chromaticity, Non-Linearities
 - Lattice Errors, Coupling, CC Roll
- Baseline Design (400 MHz), RF Requirements
- CC Longitudinal and Transverse Impedance
- Possible Exotic Schemes
- Conclusions

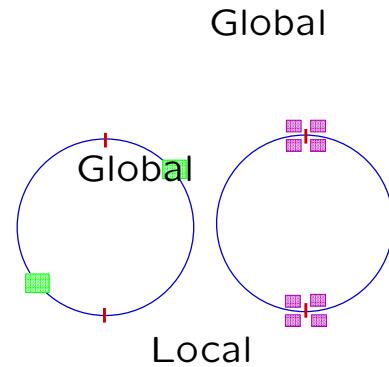
History & Motivation

- 1960: CERN/Karlsruhe - 2.86 GHz Kaon Separation
- 1991: Cornell - 1.5 GHz B-Factory (Prototype: 3×Operating Freq.)
- 1993-now: KEKB - 500 MHz B-Factory (In operation soon)
- 1996-now: ALS, APS, … Synch Light Compression
- 2000-now: FNAL - 3.9 GHz Kaon Sep., ILC Crab Crossing (1.3-3.9 GHz)
- 2005-now: LHC - 400 MHz Crab Crossing



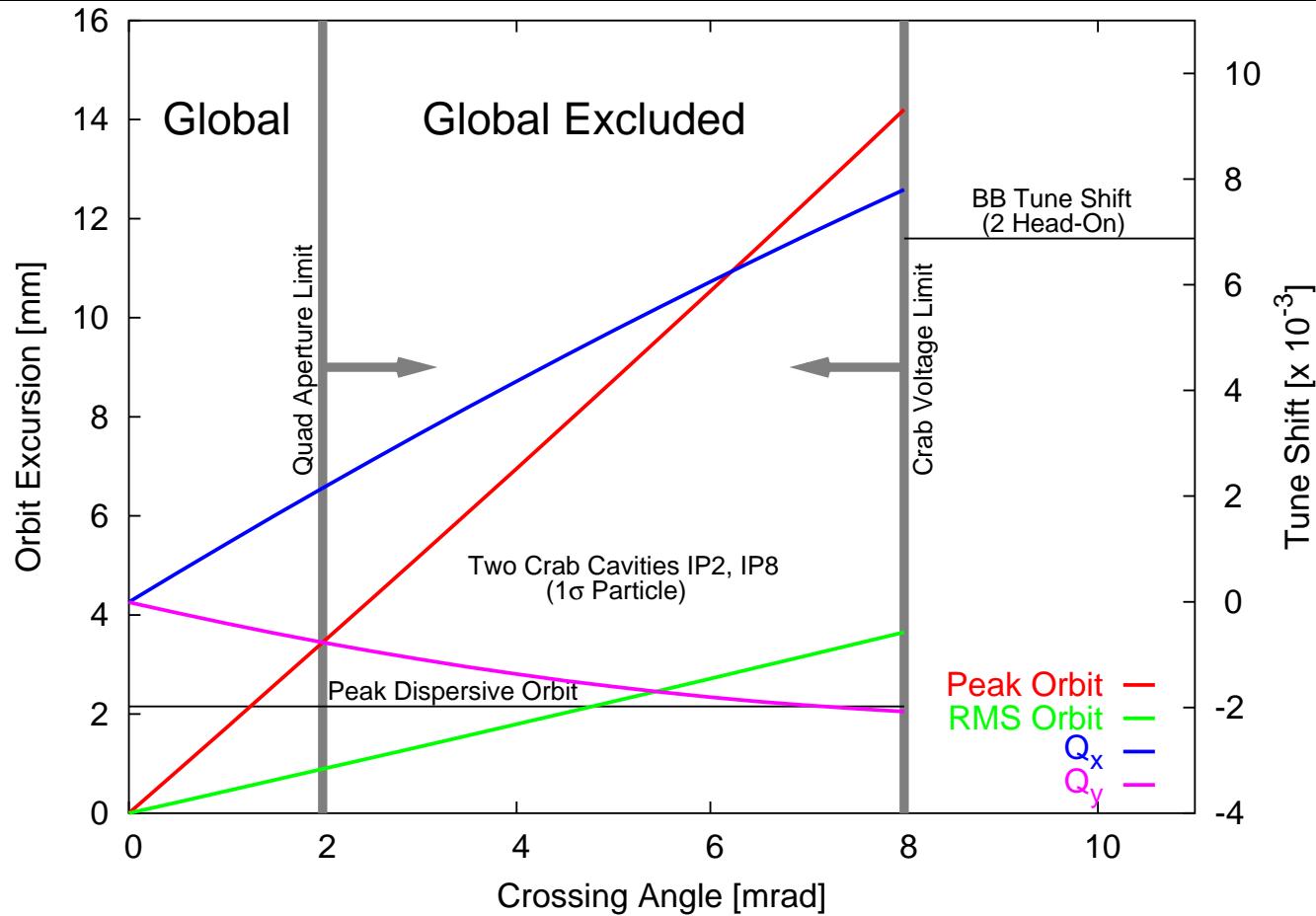
- Geometric luminosity loss
$$\frac{L}{L_0} \approx \left[1 + \left(\frac{\sigma_z}{\sigma_x^*} \tan(\theta_c/2) \right)^2 \right]^{1/2}$$
- Long range beam-beam
- Simple IR design (Sep. Quads)
- β^* reduction & flexibility

Global (Osc. Orbit) or Local (IR) Crab Compensation



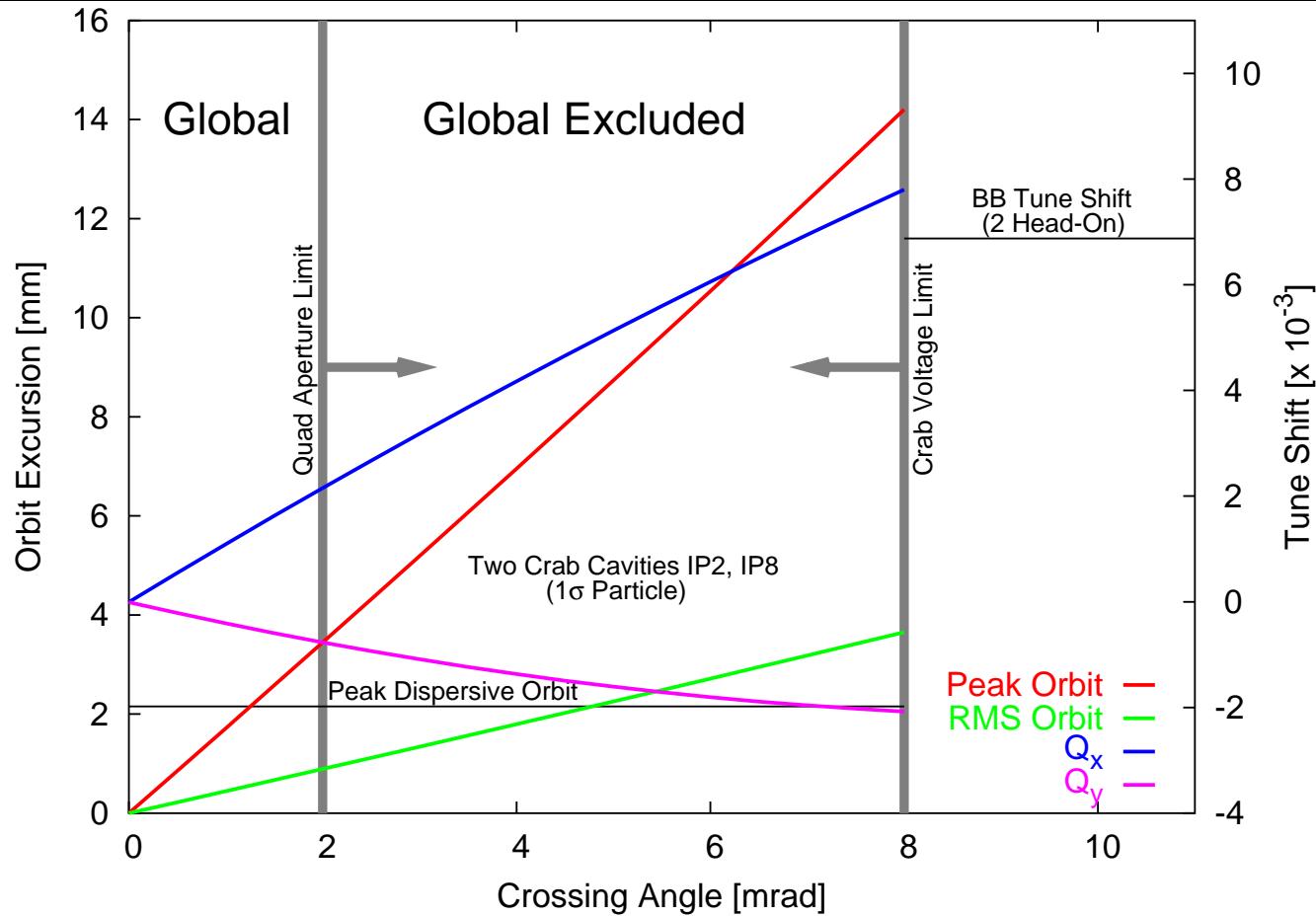
The “mrad” Question

Orbit Excursion & Tune Spread



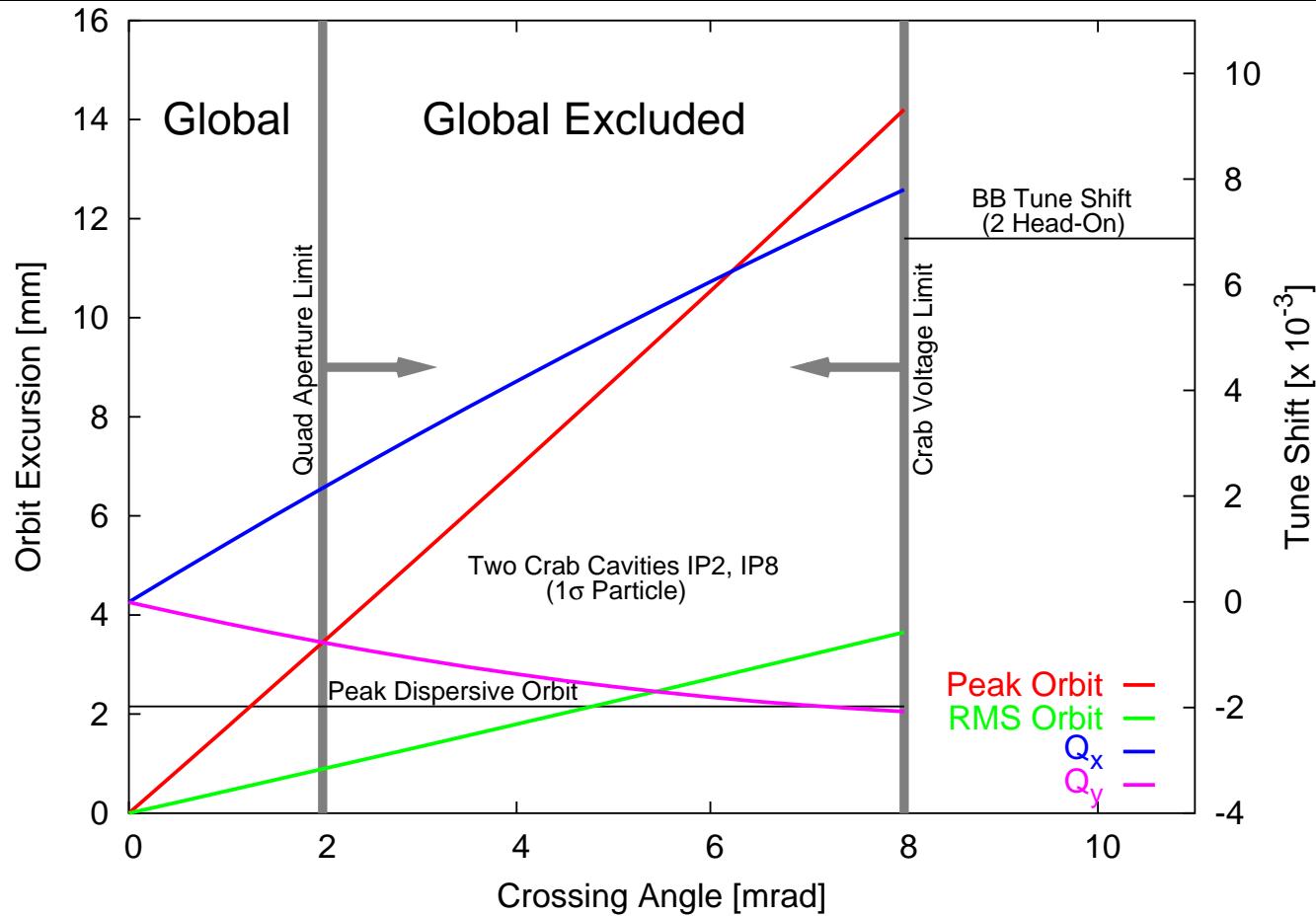
0.4-2 mrad	4-6 mrad	8 mrad
Nom. Quad-First	Sep. Quads (Exotic)	Sep. Quads (Simple)
$V_{crab} < 15$ MV Cavity Simple	$V_{crab} \sim 50\text{-}70$ MV Exotic Cavity	$V_{crab} \sim 111$ MV Voltage Limit

Orbit Excursion & Tune Spread



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Orbit Excursion & Tune Spread



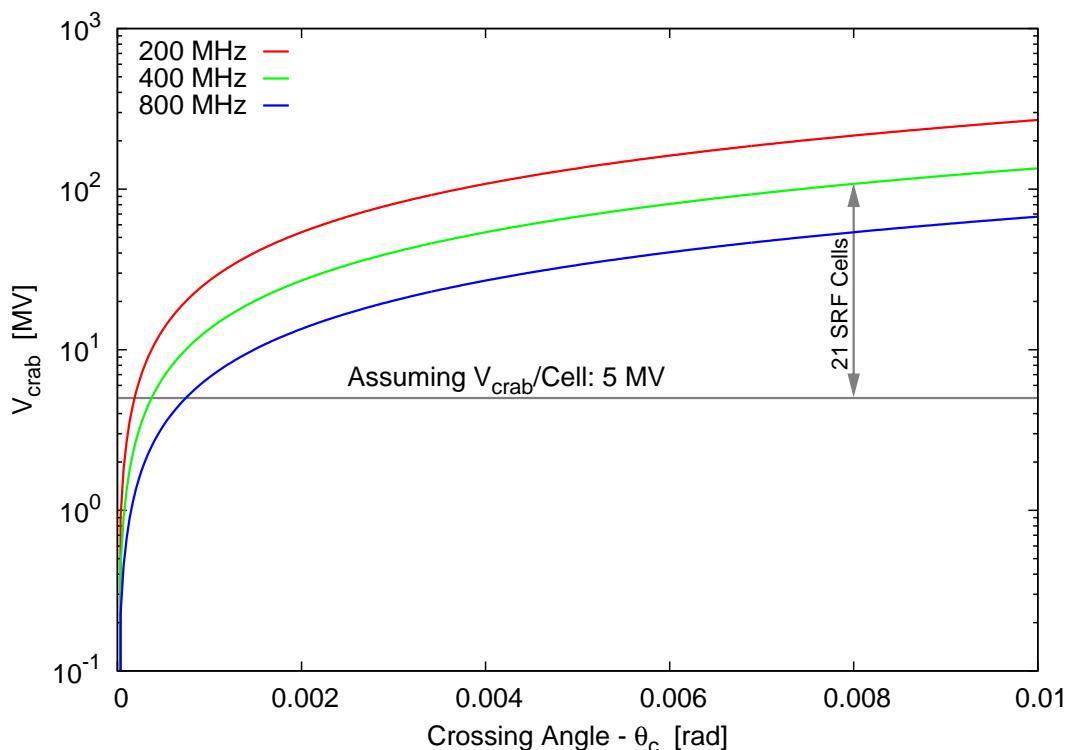
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Crab Voltage Requirement

$$V_{crab} = \frac{cE_0 \tan(\theta_C/2)}{\omega_{RF} \sqrt{\beta_{crab} \beta^*}} \quad \{\sigma_z \ll \lambda_{RF}\}$$

X-Angle	1 mrad	5 mrad	8 mrad
200 MHz	27 MV	134 MV	216 MV
400 MHz	14 MV	67 MV	108 MV
800 MHz	7 MV	34 MV	54 MV

(Assuming $R_{12} = 31$ m)



- Reduce # Cavities
 - Increase Real-Estate Gradient
 - Increase β_x^* & β_x^{crab} (**Flat Beam**)
 - Reduce bunch length (\$\$\$) + Increase Frequency (x2)
- Lower X-Angle
 - Reduce Transverse Dimensions
 - Exotic Shapes

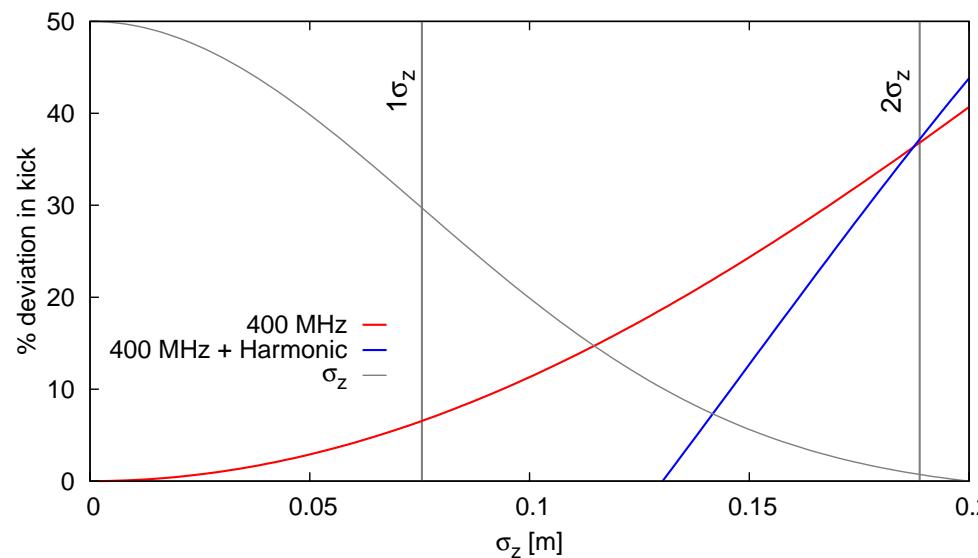
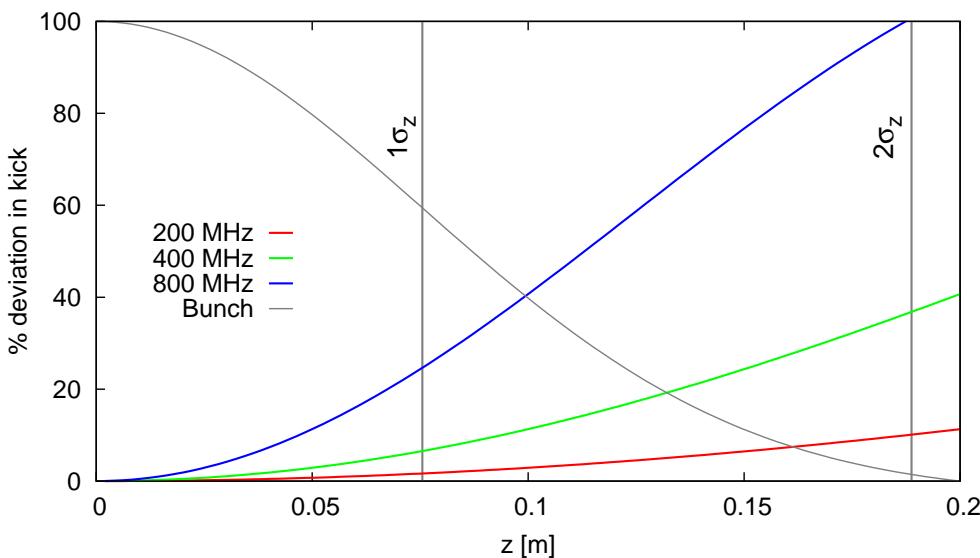
RF Curvature

Deviation From Linear Kick:

$$\begin{aligned}\Delta x' &\approx \frac{1}{R_{12}} \sin(2\pi z/\lambda_{RF}) \\ &\approx \frac{2\pi}{\lambda} \left[z - \frac{2\pi^2 z^3}{3\lambda^2} + \dots \right]\end{aligned}$$

Luminosity Reduction:

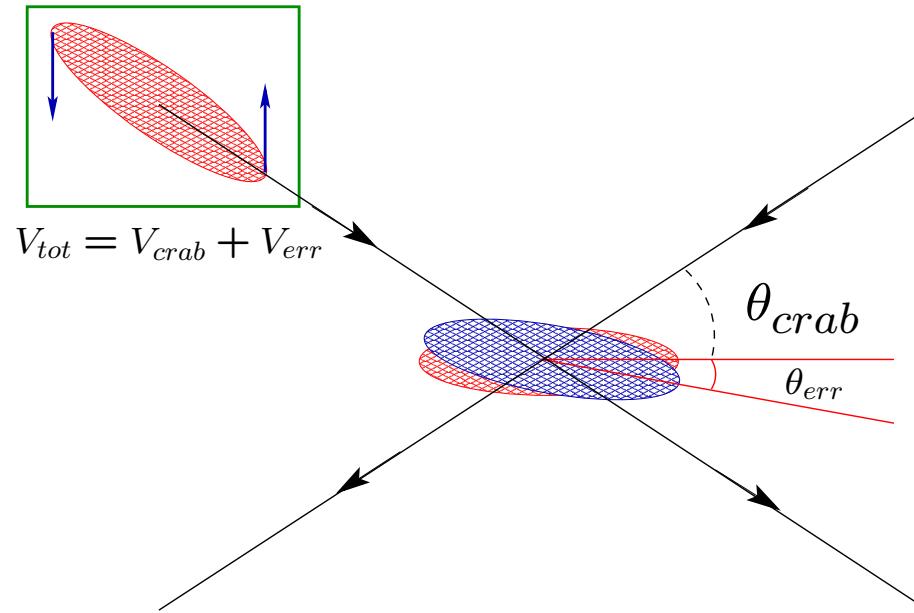
$$\begin{aligned}R &= \frac{\sqrt{1 + \cos(\theta_c)}}{\sqrt{2\pi}\sigma_z} \int_{-\infty}^{\infty} \exp\left(-\frac{s^2(1 + \cos(\theta_c))}{2\sigma_z^2} - \frac{\sin(\theta_c/2)(-k_c s + \sin(k_c s))^2}{k_c^2 \sigma_x^2}\right) \\ &\approx 25 - 30\% \quad (8 \text{ mrad, } 400\text{MHz})\end{aligned}$$



Noise Tolerances

Amp. jitter introduces additional X-Angle:

$$\Delta x' = \frac{\theta_c}{2R_{12}} \left(\frac{\Delta V_\perp}{V_\perp} \right) z$$
$$\frac{\Delta V_\perp}{V_\perp} \approx \frac{\theta_{err}}{\theta_c} \ll \frac{1}{\tan(\theta_c/2)} \frac{\sigma_x^*}{\sigma_z}$$

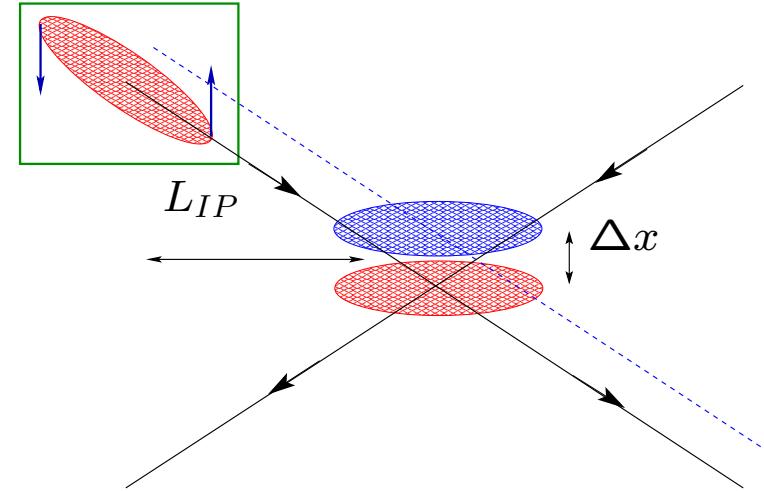
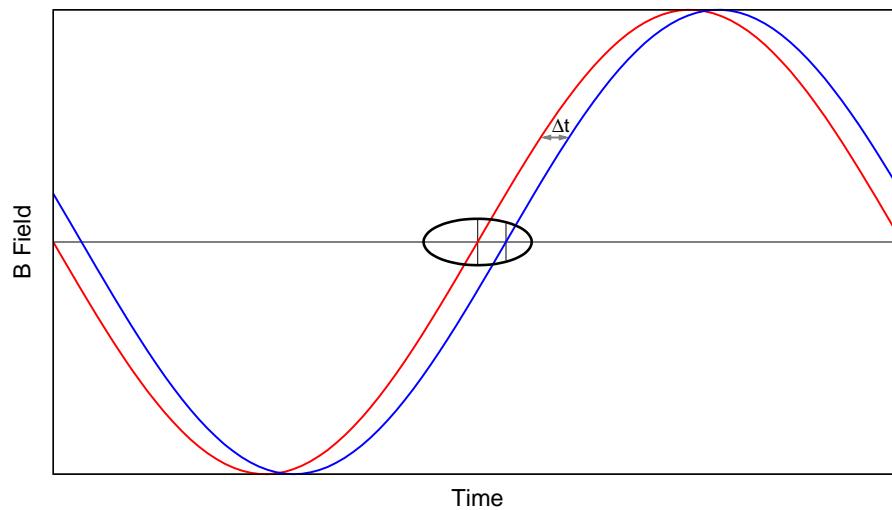


X-Angle: 8 mrad $\rightarrow \frac{\Delta V_c}{V_c} < 0.04\% \rightarrow \theta_{err} \approx 3\mu rad$ (Available Today)

Noise Tolerances

Phase jitter introduces random offset:

$$\Delta x_{IP} = \frac{c\theta_c}{\omega_{RF}} \delta\phi$$
$$\left(\frac{\Delta\epsilon_x}{\Delta t}\right)_{BB} \approx n_{IP} f_r \frac{8\pi^2 \xi^2}{\beta_x^*} (\Delta x)^2, \quad \left(\frac{\Delta\epsilon_x}{\Delta t}\right)_{CC} \approx n_{IP} \frac{f_r}{2\beta^*} \left(\frac{c\theta_c}{2\omega} \Delta\phi_c\right)^2$$



X-Angle: 8 mrad & $\Delta\epsilon/\Delta t = 10\%/\text{Hr}$

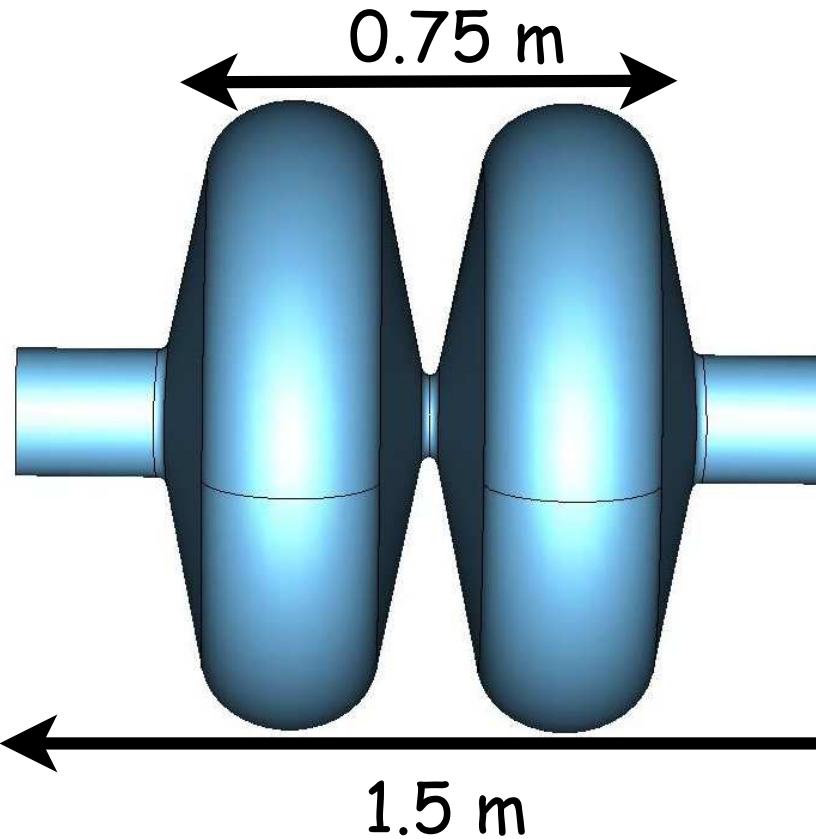
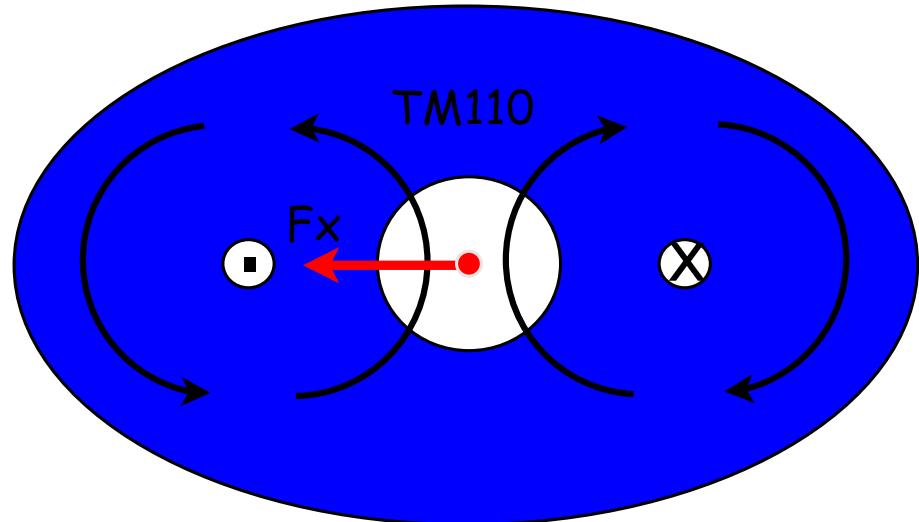
$\Delta\phi_{BB} \leq 0.001^\circ$, $\Delta\phi_{CC} < 10^{-4}$ deg ($\Delta x/\sigma_x^* < 10^{-3}$ perhaps too pessimistic)

$\Delta\phi_{rel} = 0.003^\circ$ (feasible \rightarrow ILC)

Tolerances maybe relaxed due to transverse feedback

See Ohmi's talk

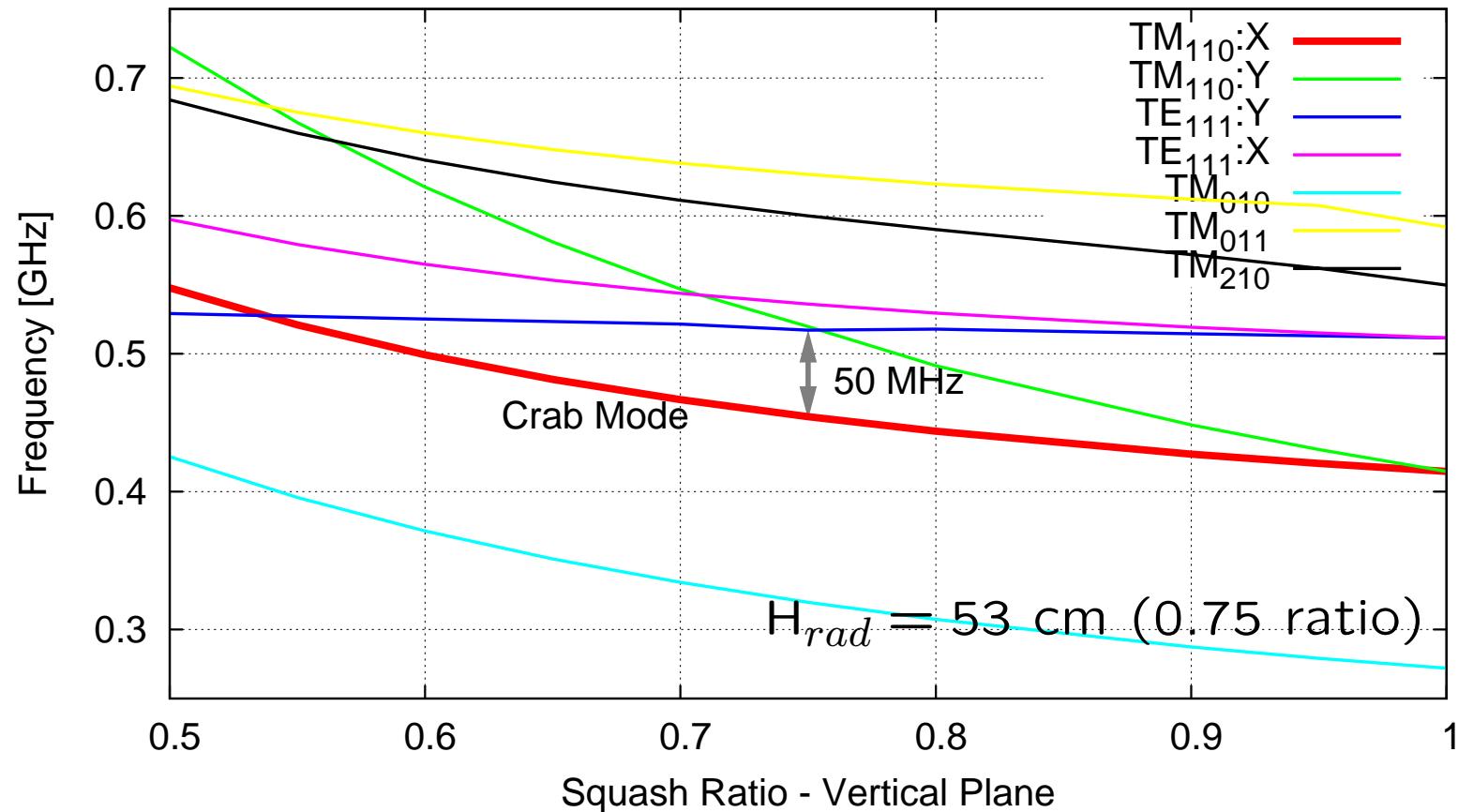
Baseline: Elliptical & Squashed



Half Cell Length, $L = \frac{\lambda\beta}{4}$	18.75 [cm]
Two Cells + Beam Pipe	~ 1.5 [m]
Horizontal Eq. Radius, R_{iris}	53 [cm]
Horizontal Eq. Radius, R_{iris}	37.5 [cm]
Squash Ratio	0.75
Beam Pipe Radius	15 [cm]
Wall Angle, α	~ 6 [deg]
Equator Dome Radius	12.0 [cm]
Cavity Beta, $\beta = \frac{v}{c}$	1.0

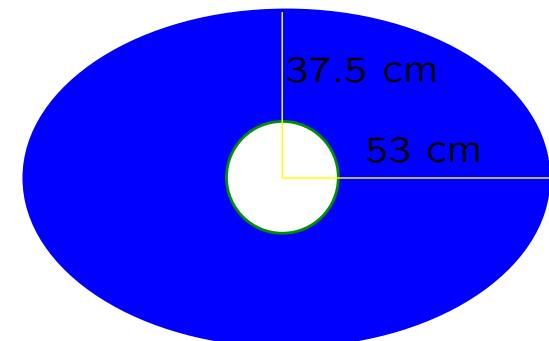
- Two Cells ~ 5 MV/Structure
- LOM + HOM Couplers
- Polarize for mode separation
- Tuners, Cryostat, ...

Parasitic Mode Separation



For $H_{rad} < 50 \text{ cm}$

- Reduce squash ratio
- Optimize cavity shape and beam pipe



Prelim RF Parameters

Quality Factor:

$$Q_0 \approx 10^9 \text{ (BCS @ 2K)}$$

$$Q_{ext} \approx 10^6 - 10^7 \text{ (Tuning & RF control)}$$

Crab Voltage:

$$V_{\perp} = \sqrt{\omega U \frac{R_{\perp}}{Q_0}}, \quad \frac{R_{\perp}}{Q_0} = \frac{1}{(kr)^2 \omega U} \int_0^L E_{z(r=r_0)} e^{ikz} dz$$

Beam Power (1 Amp):

$$P_B \approx 50 \text{ kW/mm}$$

Peak Fields ($V_{kick} = 5 \text{ MV}$):

$$E_{peak} < 25 \text{ MV/m (no limitation)}$$

$$B_{peak} < 150 \text{ Oe (Max Limit - 2200-2400 Oe)}$$

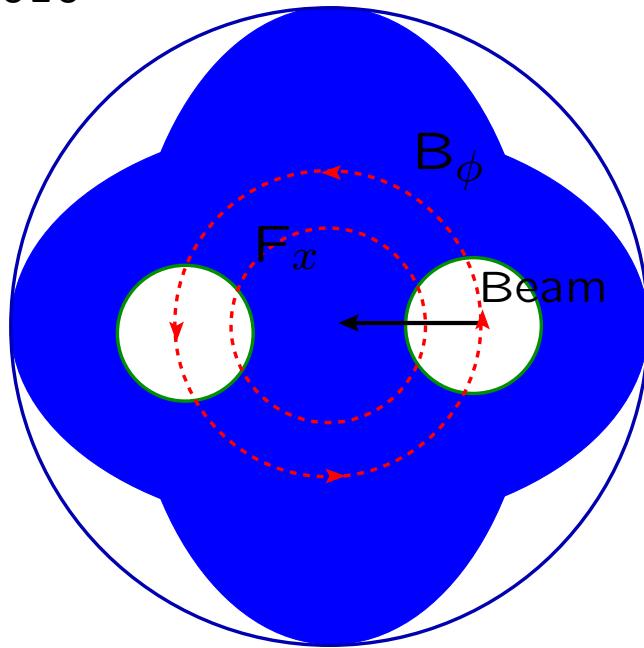
$$\text{Acc. cavities} \sim 500-700 \text{ Oe} \rightarrow 50 \text{ MV/m } E_{acc}$$

Optimization of RF parameters needed for higher gradient

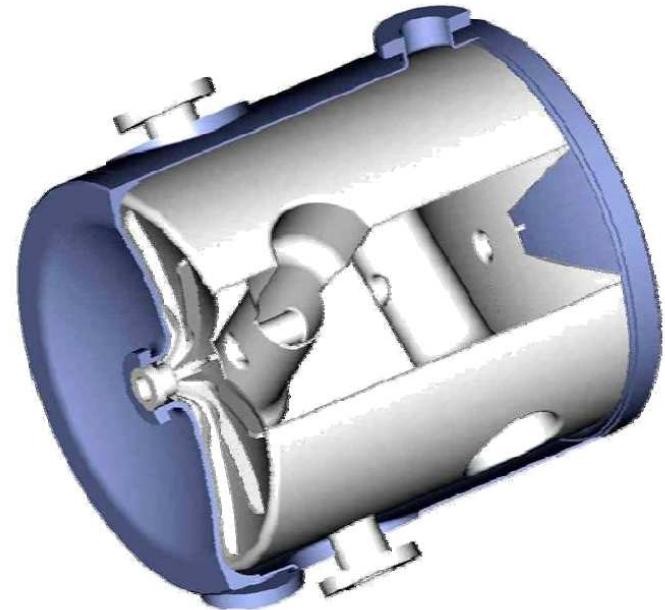
More details in J. Tuckmantel's talk.

Some Exotic Concepts

TM₀₁₀ Mode:



Spoke Cavities:



- Advantages: Smaller transverse dimensions, high R/Q, high gradient, simpler design (HOM's, couplers, etc...)
- Disadvantages: Transverse wake-fields, multipacting needs evaluation, beam loading and others

- Advantages: More compact than TM₁₁₀ cavities, mechanically stable
- Disadvantages: Complicated design (significant R&D), lower gradient (??), multipacting

Conclusions

- X-Angle scheme with crab cavities attractive
 - Recover geometric luminosity loss
 - Diminish long range beam-beam effects
 - Simple IR design (Separate Quad Channels), β^* reduction, flexibility
- Issues with RF frequency & cavity dimensions need R&D
- Noise estimates for phase tolerance looks too pessimistic
 - Multiparticle simulations for noise tolerances
 - Include machine details ($\delta E/E$, ξ_x , lattice Errors, coupling, etc..)
- R&D Effort: CERN, BNL, & LBNL (Optics, Cavity Design, RF Control, etc..)
- Benefit from ILC crab cavity activity